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**Citation for published version:**

Spencer, M & Essery, R 2016, 'Scottish snow cover dependence on the North Atlantic Oscillation index', *Hydrology research*. <https://doi.org/10.2166/nh.2016.085>

**Digital Object Identifier (DOI):**

[10.2166/nh.2016.085](https://doi.org/10.2166/nh.2016.085)

**Link:**

[Link to publication record in Edinburgh Research Explorer](#)

**Document Version:**

Peer reviewed version

**Published In:**

Hydrology research

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# 1 Scottish snow cover dependence on the North 2 Atlantic Oscillation index

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## 8 **Abstract**

9 Forecasting seasonal snow cover is useful for planning resources and  
10 mitigating natural hazards. We present a link between the North Atlantic  
11 Oscillation (NAO) index and days of snow cover in Scotland between win-  
12 ters beginning from 1875 to 2013. Using broad (5 km resolution), national  
13 scale datasets like UK Climate Projections 2009 (UKCP09) to extract na-  
14 tionwide patterns, we support these findings using hillslope scale data from  
15 the Snow Survey of Great Britain (SSGB). Currently collected snow cover  
16 data, are considered using remotely sensed satellite observations, from Mod-  
17 erate Resolution Imaging Spectroradiometer (MODIS); but the results are  
18 inconclusive due to cloud. The strongest correlations between the NAO in-  
19 dex and snow cover are found in eastern and southern Scotland, these results

20 are supported by both SSGB and UKCP09 data. Correlations between NAO  
21 index and snow cover are negative with the strongest relationships found for  
22 elevations below 750 m. Four SSGB sites (two in eastern Scotland, two in  
23 southern Scotland) were modelled linearly with resulting slopes between -6  
24 and -16 days of snow cover per NAO index integer value. This is the first  
25 time the relationship between NAO index and snow cover duration has been  
26 quantified and mapped in Scotland.

27 **Keywords:** Climate, North Atlantic Oscillation, snow, Scotland

## 28 **Introduction**

29 Snow is important in Scotland for water resources, e.g.: the largest instrument-  
30 measured flow in Scotland's largest catchment, the River Tay, was partly caused  
31 by snowmelt (Black and Anderson, 1994). Dunn et al. (2001) show that snow can  
32 contribute to river baseflow until July, as melted snow takes a generally slower  
33 sub-surface pathway to a water course. Also, Gibbins et al. (2001) discuss the  
34 importance of snowmelt for freshwater invertebrate habitat in the Cairngorms.  
35 Knowledge of snow extent and duration can help understand habitat change (Trivedi  
36 et al., 2007), and global snow cover data are collated by the Intergovernmental  
37 Panel on Climate Change (Vaughan et al., 2013).

38 The North Atlantic Oscillation index (NAO) is the normalised pressure dif-  
39 ference between the Icelandic low and the Azores high (Walker and Bliss, 1932).  
40 Positive NAO phases are typified by strong westerly winds carrying moist warm  
41 air from the Atlantic, with negative NAO phases bringing colder air masses from  
42 the east (Hurrell, 1995; Simpson and Jones, 2014). Logically then, the NAO in-  
43 dex could indicate the duration of snow cover as colder weather means a greater  
44 chance of snow and its persistence, but this signal may be confused by positive  
45 NAO phases bringing increased precipitation.

46 NAO index relates to hydrological processes: Hannaford et al. (2005) show  
47 river flow and NAO index have strong positive correlations (e.g. River Nith: 0.63)  
48 in the north and west of the UK, but eastern catchments had a weaker correlation  
49 (e.g. River Tweed: 0.38). Harrison et al. (2001) has suggested an association  
50 between snow cover and NAO phase is likely. While Trivedi et al. (2007) found  
51 snow cover, in the Ben Lawers region north of Loch Tay, at 300 m and below to be  
52 significantly ( $p < 0.05$ ) negatively correlated with NAO index, between -0.55 and

53 -0.38, with lower elevations having a stronger relationship. Trivedi et al. (2007)  
54 also found no correlation between NAO index and falling snow, perhaps because  
55 it is often cold enough for snow to fall during a Scottish winter, irrespective of  
56 NAO phase, but during positive NAO phases the warmer air causes snow to melt  
57 and only with the colder temperatures associated with negative NAO indices does  
58 snow lie for longer. There has been more research on snow cover links to the NAO  
59 index in continental Europe, where snow cover has a greater impact (e.g. Scherrer  
60 et al. 2004; Kim et al. 2013; Bednorz 2004; Beniston 1997; Lopez-Moreno et al.  
61 2011).

62 There has recently been an increase in winter variability of the NAO phase  
63 (Hanna et al., 2014; Osborn, 2006), including a record low NAO index in 2009/10  
64 (Osborn, 2010). The 2009/10 low occurred the same year as an exceptionally cold  
65 and snowy winter in the UK (National Climate Information Centre, 2010; Prior  
66 and Kendon, 2011). Goodkin et al. (2008) link variability in the NAO index to  
67 northern hemisphere mean temperature and state any future predictions should  
68 take this into account.

69 The UK Met Office are beginning to more successfully forecast seasonal NAO  
70 indices (Scaife et al., 2014), which could be used to plan for heavy snow in ad-  
71 vance of a winter season. For a forecast made on the 1st November Scaife et al.  
72 (2014) give a correlation value of 0.62 (significant at 99 %) between forecast and  
73 observed DJF NAO index for the years 1993 to 2012.

74 We hypothesise that snow cover in Scotland is negatively correlated to the  
75 NAO index. We establish this by looking at nationwide snow cover datasets, be-  
76 fore further investigating relationships at a hillslope scale, using case studies with  
77 more detailed data available. Our paper is laid out as follows: methods and data,

78 results, discussion and conclusion. The methods and results sections are split by  
79 dataset.

## 80 **Data and methods**

81 We used NAO index data from the Climate Research Unit, University of East  
82 Anglia (Undated) and Osborn (Undated) as these comprise a long and definitive  
83 record (Table 1). The longest data series of Scottish snow cover are from UK Met  
84 Office stations which record snow presence at a given point at 09:00 hours UTC  
85 each morning; the longest of these is Braemar which has recorded since 1927  
86 (Harrison et al., 2001). 96 % of UK Met Office snow recording stations lie below  
87 300 m elevation (Spencer et al., 2014) and so are unrepresentative of the 31 %  
88 of Scottish landmass that is higher (Spencer et al., 2014). These UK Met Office  
89 station data are used by proxy via the UK Climate Projections 2009 (UKCP09)  
90 snow cover dataset (Met Office, Undated). Table 1 shows a non definitive list of  
91 Scottish snow cover datasets, which are all used within this study.

92     Snow in Scotland is often ephemeral and so metrics like average snowline and  
93 maximum snow cover extent are meaningless because each winter can see many  
94 snow accumulation and melt cycles. We solved this by using a count of the days  
95 of snow cover during a given time period. We define a winter period for snow  
96 cover as November to April to help differentiate the snowiest winters, while being  
97 short enough to not discount many SSGB records, as some are missing (Spencer  
98 et al., 2014). A short winter period (e.g. DJF) would mean, particularly at higher  
99 elevations, a count of days with snow lying would result in saturated values of  
100 days of snow cover, i.e. there cannot be any more than 31 days with snow lying  
101 in January, but 31 days of cover is often the case at higher elevations in Scotland.

102 Using a six month period will help identify the snowiest winters, where greater  
103 snow depths take longer to melt. Analysis was undertaken using the R language  
104 (R Core Team, 2015).

## 105 **NAO**

106 NAO index data have been averaged (mean) over DJFM, as described by Osborn  
107 et al. (1999), to better represent the prevailing winter NAO index. Note this winter  
108 period is different to the NDJFMA period used for snow cover. Fig. 1; shows the  
109 predominant NAO index is positive, aligning with our understanding that the UK  
110 is more likely to experience weather systems from the west.

## 111 **Bonacina**

112 The Bonacina snow index was originally compiled by Leo Bonacina (Bonacina,  
113 1966) and is now maintained as a website (O'Hara and Bonacina, Undated). Each  
114 winter is subjectively categorised into one of four groups: Little, Average, Snowy  
115 and Very Snowy. This is based on how much snow fell and how much of the coun-  
116 try it covered using anecdotal data from weather journals, UK Met Office stations  
117 and websites. Other snow cover datasets used in this work state the number of  
118 days of snow cover over a given time period. Bonacina data has been included  
119 because it covers a much longer time period than the other snow cover datasets  
120 (Table 1).

121 Mean DJFM NAO index values are grouped by Bonacina categories. The dif-  
122 ferences between groups of the NAO index are compared visually using boxplots  
123 (Fig. 2) and statistically using an ANOVA and Tukey honest significant differ-  
124 ences (HSD) (Yandell, 1997) tests, the latter to account for family-wise analysis

125 (Table 2).

## 126 **UK Climate Projections 2009 (UKCP09)**

127 The UKCP09 snow dataset comprises a 5 km resolution raster image for each  
128 month, where each grid value represents the number of days snow cover for that  
129 cell. November to April data are available from 1971/72 until 2005/06. These  
130 were interpolated from UK Met Office station data by Perry and Hollis (2005).  
131 These data have been shown (Spencer et al., 2014) to poorly represent reality at  
132 higher elevations. The dataset is used here to identify regions for more detailed  
133 exploration. UKCP09 snow data were downloaded from Met Office (Undated).  
134 The November to April sum of days of snow cover are compared using a Pearson  
135 correlation to the mean DJFM NAO index. The resulting Pearson correlation is  
136 plotted (Fig. 3) to show spatial patterns.

## 137 **Snow Survey of Great Britain (SSGB)**

138 The SSGB reported at 145 stations in Scotland at differing times between 1945  
139 and 2007, but some records are missing (Spencer et al., 2014). Stations were  
140 selected for inclusion in this study based on whether they recorded for all months  
141 between November to April. The number of SSGB stations meeting this criterion  
142 each year is shown in Fig. 4. The gaps in the number of reporting stations are  
143 because data are missing from part of these years. This is directly related to only  
144 including stations that recorded all months between November and April each  
145 winter.

146 SSGB observers recorded the elevation of snowline on visible hillslopes sur-  
147 rounding each station. We constructed snow accumulation curves, where the num-



ber of days snow cover over a range of elevations are shown. These accumulation curves are split by NAO index and shown in Fig. 5. The primary purpose of these curves is to assess the break point between higher and lower elevation snow cover.

Three groups of individual stations are also considered, again meeting the criterion of six months of record for a winter; group one: stations with the longest record, group two: stations in the east of Scotland, group three: a single station on Orkney. Details of these stations are shown in Table 3 and the location in Fig. 6. The second and third groups have much shorter records than the longest-running stations, they have been included to help test whether eastern sites are more likely to have snow cover influenced by the NAO index and whether the UKCP09 snow data are a good approximation of snow cover. The groups of stations in Table 3 are compared to the NAO index using a high and low elevation split (at 750 m) and a Loess (locally weighted scatterplot smoothing) (Cleveland, 1979; Cleveland and Devlin, 1988) with 95 % confidence limits (Fig. 7 and 8).

Stations from Table 3, judged by eye to have a Loess close to a straight line, are plotted in Fig. 9 with linear models, showing the Pearson correlation value and line parameters (slope and intercept). This allows us to relate a given NAO index to an expected number of days snow cover duration for a high or low elevation.

## **Moderate Resolution Imaging Spectroradiometer (MODIS)**

There are two main methods for remote sensing of snow; microwave and visible. Using microwave to detect snow cover is very challenging in mountainous terrain (Snehmani et al., 2015) or when snow is wet (Rees and Steel, 2001). Snehmani et al. (2015) review methods that improve microwave assessment of snow cover, but these are data and computing intensive and trialling them in Scotland where

172 it is very cloudy, wet and mountainous is beyond the scope of this study. Some  
173 snow cover datasets amalgamate different data sources, including Robinson et al.  
174 (Undated) and Foster et al. (2011), which have grid resolutions of 190.5 km and  
175 25 km respectively; these are coarse grids which would miss spatial detail. Foster  
176 et al. (2011) found that Earth Observation System Moderate Resolution Imaging  
177 Spectroradiometer (MODIS) outperformed microwave snow detection in cloud  
178 free areas. MODIS is freely available on a 500 m grid at a twice daily resolution,  
179 and there are some reanalysis products, e.g. Notarnicola et al. (2013), which re-  
180 calculate snow cover at a 250 m grid, but are only available for the Alps. MODIS  
181 data are used in this study because of the temporal overlap with SSGB data and  
182 fine resolution of the dataset. The MODIS dataset chosen was the tile set which  
183 records as binary whether snow covered each cell, rather than the fractional or  
184 albedo datasets. Coverage of Scotland is split across two tiles; these were down-  
185 loaded from the National Snow and Ice Data Centre (Hall et al., 2006) for both the  
186 Aqua (2002-07-04 onwards) and Terra (2000-02-24 onwards) satellites. Each pair  
187 of tiles were merged together and reprojected to the British National Grid using  
188 GDAL (GDAL Development Team, 2015). Using GRASS GIS software (GRASS  
189 Development Team, Undated), a combination of both satellites was created to re-  
190 duce the incidence of cloud pixels by approximately 15 %. This method was only  
191 possible from 2002-07-04 onwards, when the Aqua satellite became operational.  
192 Prior to this the Terra satellite alone was used, creating a dataset containing full  
193 winters from 2000/01 until 2013/14. These November to April period data were  
194 summed and correlated against the DJFM NAO mean index, presented in Fig. 10a.  
195 Fig. 10b shows the equivalent analysis, but repeated for cloud cover observed by  
196 MODIS.

## 197 **Data comparison**

198 To relate SSGB station and national results, Pearson correlations from SSGB,  
199 MODIS and UKCP09 are compared. Values from MODIS and UKCP09 rasters  
200 were extracted at SSGB station locations and are shown together in Table 4.

## 201 **Results**

### 202 **Bonacina**

203 Fig. 2 shows boxplots of the difference between DJFM NAO index as grouped  
204 by the Bonacina classification. A general trend can be seen where less snowy  
205 winters have a more positive NAO index. This is demonstrated statistically using  
206 ANOVA (F value = 25.07) and a Tukey HSD analysis (Table 2) where each pair  
207 is shown with a best estimate of difference and significance value. All pairs are  
208 different at greater than 5 % significance, except Very Snowy - Snowy. This could  
209 be a product of the Very Snowy small sample size, where the Tukey HSD test  
210 performs less well.

### 211 **UKCP09 snow**

212 Fig. 3 shows some strongly negatively correlated areas of Scotland. The strongest  
213 correlations are in the south west and along the east coast. Areas of poor correla-  
214 tion are predominantly in central and northern mainland Scotland and Orkney.

## 215 **SSGB**

216 Fig. 5, showing SSGB snow accumulation curves, displays a marked difference  
217 in duration of snow cover at all elevations between winters with the highest and  
218 lowest NAO indices, with positive NAO phases having less snow cover than neg-  
219 ative NAO phases. Below 750 m the difference in days of snow cover as elevation  
220 increases are broadly linear, while above 750 m the relationship is unclear, with  
221 lines crossing. This 750 m change-point is used to distinguish between high and  
222 low snow cover for the SSGB station analysis.

223 Individual SSGB stations with the longest record of complete winters and  
224 some other stations are considered (Table 3). Other stations, in the east and  
225 Orkney, were used to investigate the more extreme correlations between the NAO  
226 index and UKCP09 snow data (Fig. 3), accepting that they do not have the longest  
227 records. These results corroborate what is shown in the UKCP09 snow results  
228 (Fig. 3), that south western sites like Forrest Lodge (Fig. 7) show a negative  
229 correlation with the NAO index. This is repeated in Fig. 8 where eastern sites,  
230 Crathes and Whitehillocks, show a strong relationship to the NAO index. Also in  
231 line with the UKCP09 results, Stenness, chosen because of a poor UKCP09 snow  
232 correlation to the NAO index, shows a weak relationship to NAO index (Fig. 8).

233 SSGB stations Crathes, Eskdalemuir, Forrest Lodge and Whitehillocks have  
234 been plotted with a linear regression line, Fig. 9. Line slopes vary from -7 to  
235 -14 days for higher elevations and from -6 to -16 days for lower elevations. As  
236 can be seen in Fig. 5 to 8 the NAO index has a larger impact at lower elevations,  
237 but Pearson correlation values are variable; this could be a function of stations  
238 not observing the same time periods and hence some sampling produces better  
239 correlations than others. None of the SSGB stations observed the record NAO

240 index low of winter 2009/10.

## 241 **MODIS**

242 Fig. 10 was interpolated (bilinear) to a 5 km resolution, to better show correla-  
243 tions. Fig. 10a shows a generally weak correlation between MODIS snow cover  
244 and the NAO index. The strongest correlations are in north west Scotland, with  
245 the weakest in central eastern Scotland. Orkney shows a strong correlation, in  
246 contrast to the UKCP09 and SSGb results. A small proportion of the plot, east of  
247 Edinburgh, has a very weak but positive correlation, in disagreement with Fig. 2  
248 to 9.

249 Differences from UKCP09 and SSGb results are most likely because of the  
250 frequency of cloud, as it is difficult for visible remote sensing to see through cloud.  
251 The problem is illustrated in Fig. 10b, which shows cloud cover; as interpreted by  
252 MODIS, correlated with the NAO index. The area of positive correlation exceeds  
253 the area of negative correlation. An east-west split in correlation is clearly shown,  
254 with the east coast negatively correlated to the NAO index and the west coast  
255 positively correlated to the NAO index. This will have an impact on seeing spatial  
256 snow cover trends; if we expect the east to get more days of snow cover when there  
257 is a negative NAO index, a corresponding increase in cloud cover will obscure  
258 snow observations.

## 259 **Data comparison**

260 A comparison of correlations from different datasets can be seen in Table 4. These  
261 results are summarised by Pearson correlations between datasets, UKCP09: 0.87  
262 and MODIS: -0.07, demonstrating that the SSGb and UKCP09 results corroborate

263 each other, but that MODIS results do not correlate with SSGB results.

## 264 **Discussion**

265 There is a strong correlation between UKCP09 and SSGB results, with high-  
266 lighted areas like south west Scotland and east Scotland showing strong negative  
267 correlations between snow cover and the NAO index and Orkney with no corre-  
268 lation. This indicates that UKCP09 is an appropriate method for analysing the  
269 spatial relationship between snow cover and NAO phase at a national scale. The  
270 SSGB data have shown the stronger correlation between the NAO index and snow  
271 cover at lower elevations. We believe this is because lower elevations have more  
272 transient snow as they are generally warmer than higher elevations and so snow  
273 will be less likely to fall and lying snow will more readily melt. This makes snow  
274 in these areas susceptible to even small changes in temperature. Perhaps most im-  
275 portantly: the persistence of snow at lower elevations is less, because increases in  
276 temperature from westerly air flows have a greater impact on areas that are closer  
277 to melt. This low elevation correlation is supported, by proxy, by the Bonacina  
278 index correlation to the NAO index, Fig. 2, as the majority of Great Britain is low  
279 lying, so the Bonacina index is more likely to reflect the more common (lower)  
280 elevation zone than more remote mountain areas. Our correlations of NAO index  
281 and snow cover are weaker for higher elevations, which are often cold enough  
282 for deeper snow to accumulate and take longer to melt for a wider range of typ-  
283 ical winter temperatures. The most recent example of this was winter 2013/14,  
284 which was comparatively mild and very wet, but vast quantities of snow fell at  
285 higher elevations in Scotland (Kendon and McCarthy, 2015). Kendon and Mc-  
286 Carthy (2015) discuss a lapse rate of approximately 6 °C/km between Aviemore

287 and Cairngorm summit, which was linked to the persistent Atlantic weather type  
288 and absence of temperature inversions. This lapse rate is higher than the long-  
289 term (1983 to 2008) average of 5.2 °C/km for Aviemore and Cairngorm chair lift  
290 calculated by Burt and Holden (2010), helping to explain the depth and duration  
291 of snow cover accumulated that winter.

292 Inland areas generally have a poorer correlation with the NAO index. As much  
293 of this area is high in elevation this can partly be attributed to it being cold enough  
294 for snow to accumulate and persist, irrespective of the NAO index. These con-  
295 tinental areas may also be dominated more by local weather systems and micro-  
296 climates, enabling snow to persist for longer.

297 Those stations that showed a more easily defined relationship with a Loess  
298 have had linear models fitted (Fig. 9), with Pearson correlation values, from -0.29  
299 to -0.5. This range of results could be explained by micro-climates having a bigger  
300 impact on snow cover than long-term weather patterns. This would be especially  
301 true on the east side of the Cairngorms, where wind (predominantly westerly)  
302 driven snow often accumulates on eastern slopes and can take a long time to melt.  
303 These spatial local discrepancies can also be temporal, given that the SSGB sites  
304 did not all observe the same winters, some may have been more closely correlated  
305 with the NAO index than others. The obvious solution is to consider the results  
306 from Fig. 5, which average over a greater number of SSGB stations, helping to  
307 reduce uncertainty.

## 308 **Conclusion**

309 Spatial variability of snow cover is a big challenge, it is difficult to observe and  
310 quantify. This is typified by the contrasting results of UKCP09 snow and MODIS

311 data correlations. We have overcome this by using disparate snow cover datasets,  
312 encompassing anecdotal type data (Bonacina index), interpolated ground observed  
313 data (UKCP09), the SSGB and satellite observations (MODIS). With the excep-  
314 tion of the MODIS analysis, these have all shown the same results: that Scottish  
315 snow cover is generally negatively correlated with the NAO index, with stronger  
316 correlations at lower elevations and in southern and eastern Scotland. Results  
317 from individual SSGB stations and UKCP09 grids correlate well demonstrating  
318 the value of UKCP09 data for national scale assessment of spatial trends. At sam-  
319 ple locations, increases in snow lying between November and April are 6 to 16  
320 days for each unit reduction in NAO index. These estimates could be used in  
321 conjunction with seasonal NAO forecasts in preparation for upcoming winters by  
322 groups like highways and local authority planners and snow sports industries.

323 As new snow datasets become available, particularly from satellite and reanal-  
324 ysis products, it will be worthwhile revisiting and updating this research to help  
325 constrain uncertainty. This will be particularly pertinent if predictions of a more  
326 volatile NAO index come to pass, as we will be able to better link snow cover  
327 to climate variability, helping our understanding of snow cover in a changing cli-  
328 mate.



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Table 1: Study data sources.

Name	Abbreviation	Reference	Type	Time span
Bonacina snowfall catalogue	Bonacina	O’Hara and Bonacina (Undated)	Classification of snowiness of UK winter	1875 onwards
UK Climate Projections 2009 snow lying grid	UKCP09	Perry and Hollis (2005)	Interpolated grid of UK Met Office station data (days per month)	1971 - 2006
MODIS satellite snow cover, daily 13 500m grid v005	MODIS	Hall et al. (2006)	Daily classified raster image	2000 onwards
North Atlantic Oscillation Index	NAO index	Osborn (Undated)	Single annual value (DJFM mean)	1821 onwards
Snow Survey of Great Britain	SSGB	(Spencer et al., 2014)	Daily observations of snowline elevation	1945 - 2007

Table 2: Tukey HSD difference in medians of NAO indices between pairs of Bonacina classes.

Pair	Difference	P value
Very Snowy-Snowy	-0.823	0.093
Snowy-Average	-0.670	0.008
Average-Little	-0.697	0.002



Table 3: Longest, eastern and Orkney SSGB stations details.

Station	Easting	Northing	Description	Complete winters
Eskdalemuir	323500	602600	Longest	46
Couligarton	245400	700700	Longest	44
Forrest Lodge	255500	586600	Longest	44
Ardtalnaig	270200	739400	Longest	39
Fersit	235100	778200	Longest	39
Drummuir	337200	844100	eastern	24
Derry Lodge	303600	793200	eastern	21
Crathes	375800	796900	eastern	20
Whitehillocks	344860	779790	eastern	27
Stenness	329800	1011200	Orkney	21

Table 4: Pearson correlations of snow cover and NAO at SSGB stations with geographically corresponding values extracted from MODIS and UKCP09 rasters.

Station	Elevation	SSGB	UKCP09	MODIS
Ardtalnaig	high	-0.20	-0.41	-0.40
Ardtalnaig	low	-0.27	-0.41	-0.40
Couligarton	high	-0.18	-0.30	-0.34
Couligarton	low	-0.10	-0.30	-0.34
Crathes	low	-0.43	-0.52	-0.33
Crathes	high	-0.37	-0.52	-0.33
Derry Lodge	low	-0.23	-0.22	-0.53
Derry Lodge	high	-0.13	-0.22	-0.53
Drummuir	high	-0.52	-0.46	-0.53
Drummuir	low	-0.52	-0.46	-0.53
Eskdalemuir	high	-0.38	-0.49	-0.30
Eskdalemuir	low	-0.38	-0.49	-0.30
Fersit	low	-0.11	-0.27	-0.53
Fersit	high	-0.25	-0.27	-0.53
Forrest Lodge	low	-0.29	-0.51	-0.48
Forrest Lodge	high	-0.32	-0.51	-0.48
Stenness	high	0.02	-0.05	-0.51
Stenness	low	0.02	-0.05	-0.51
Whitehillocks	high	-0.41	-0.55	-0.54
Whitehillocks	low	-0.50	-0.55	-0.54

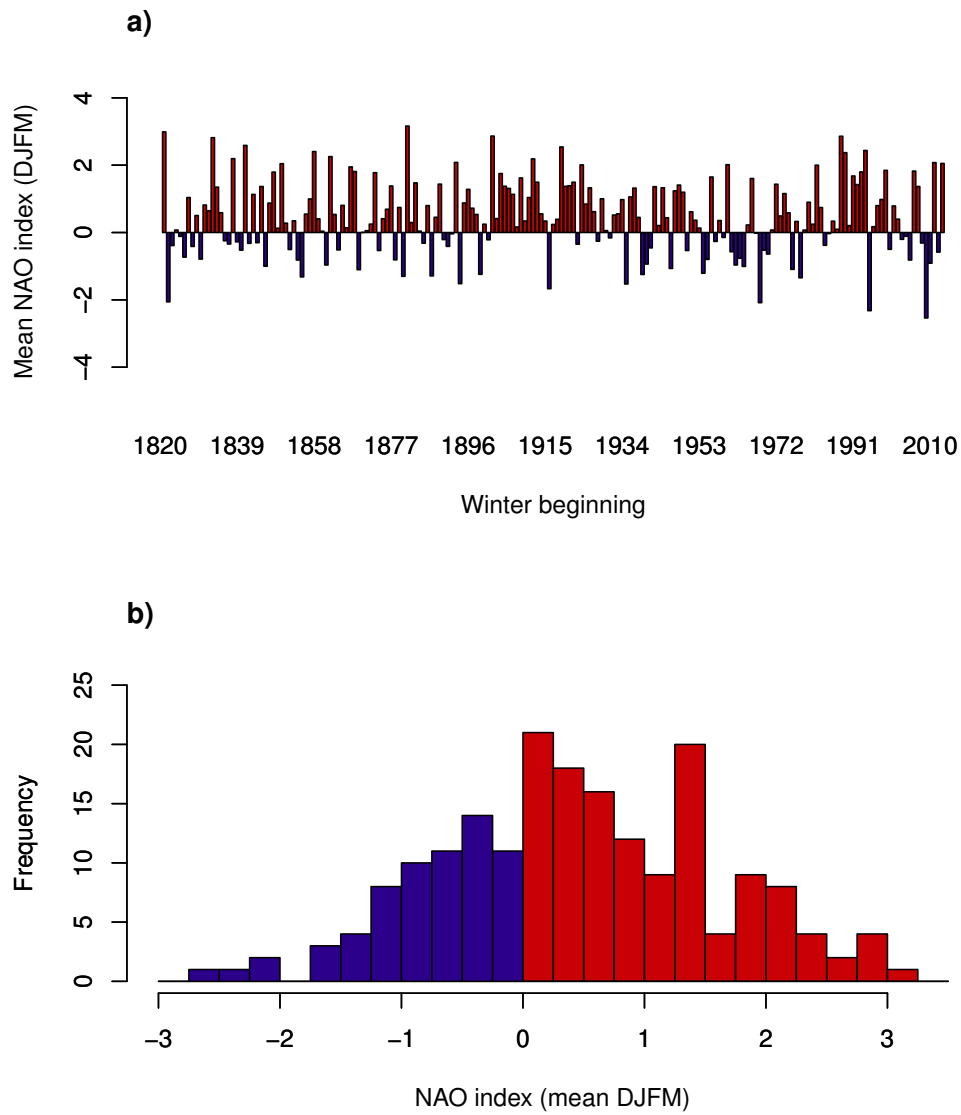


Figure 1: Mean DJFM NAO index shown: a) through time, b) as a histogram. Positive index: red, negative index: blue.

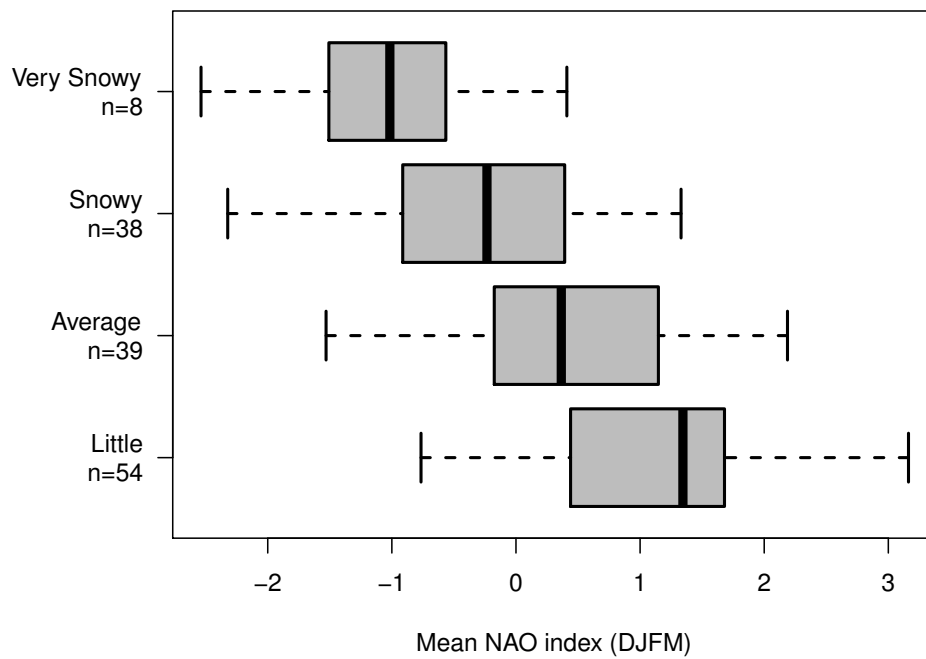


Figure 2: Boxplots (median, upper and lower quartiles and range) showing winter NAO index grouped by Bonacina snowiness categories.

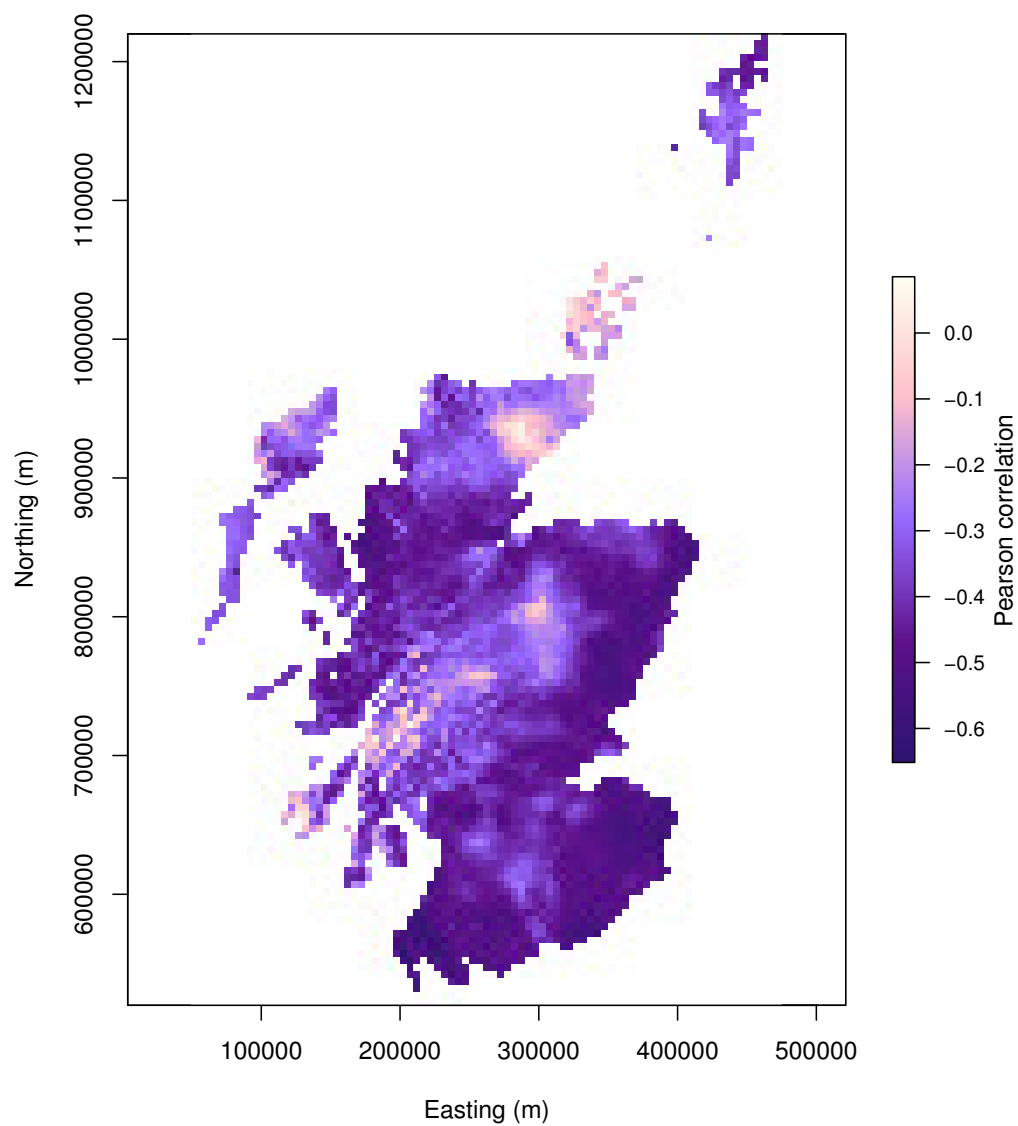


Figure 3: Map of Pearson correlation values between UKCP09 snow and the NAO index. Contains Met Office data ©Crown copyright and database right 2015.

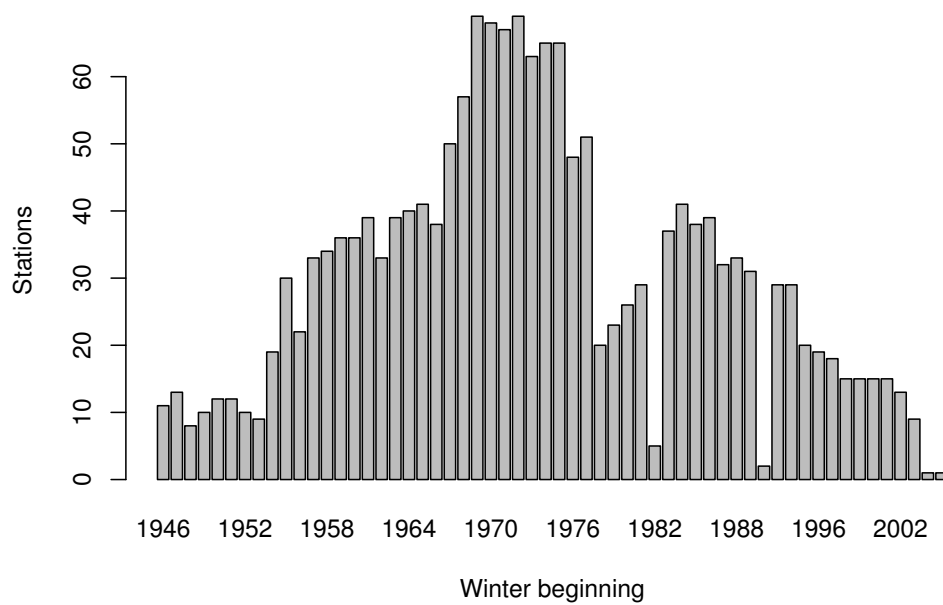


Figure 4: Number of SSGB stations each year recording all six months between November and April.

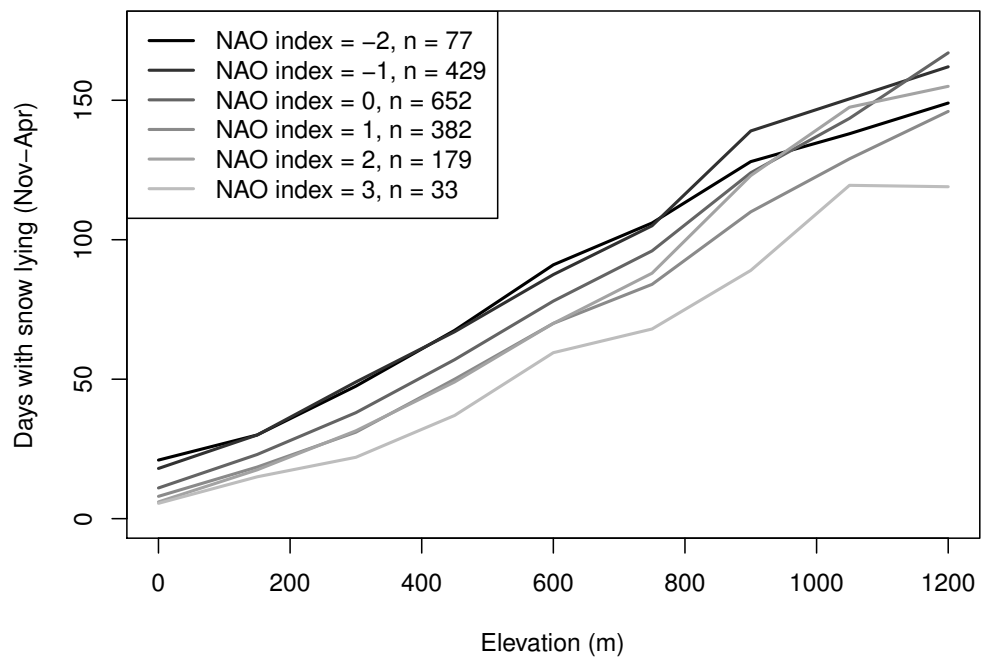


Figure 5: Snow cover duration curves derived from SSGB data between 1946 and 2006 (Nov to Apr), grouped by (rounded) mean DJFM NAO index.

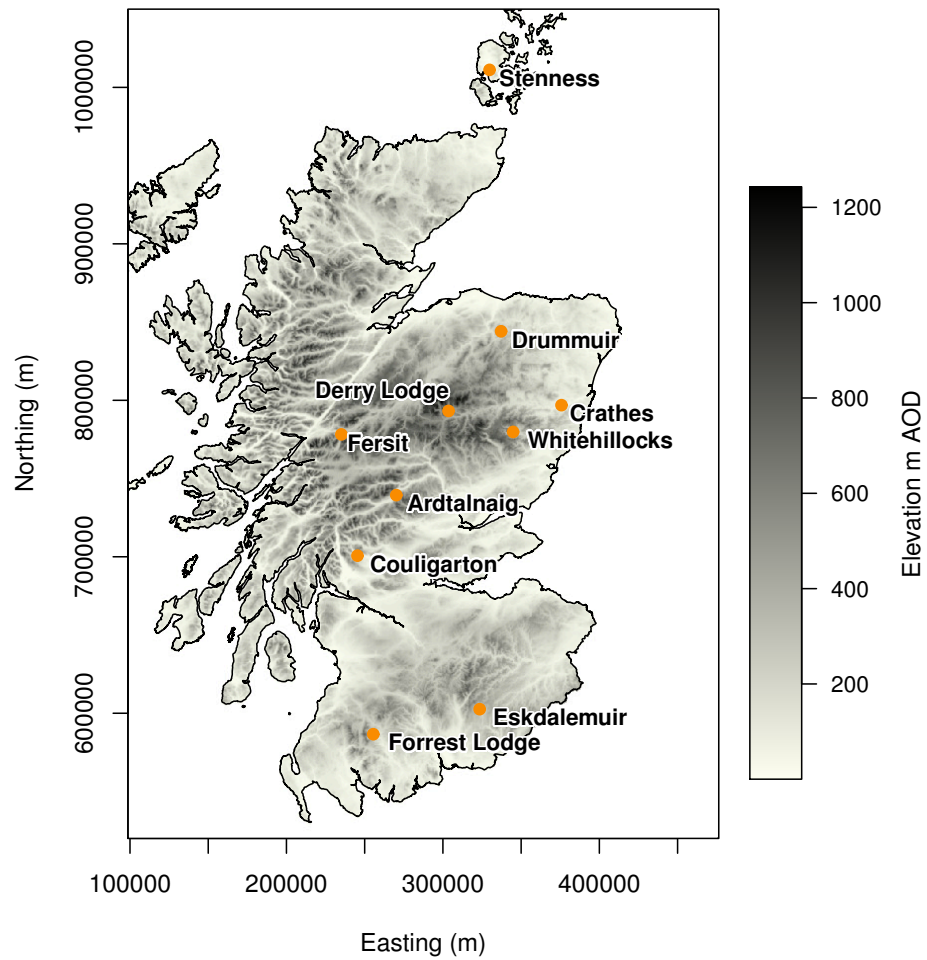


Figure 6: SSGB station locations. Contains Ordnance Survey data ©Crown copyright and database right 2015.



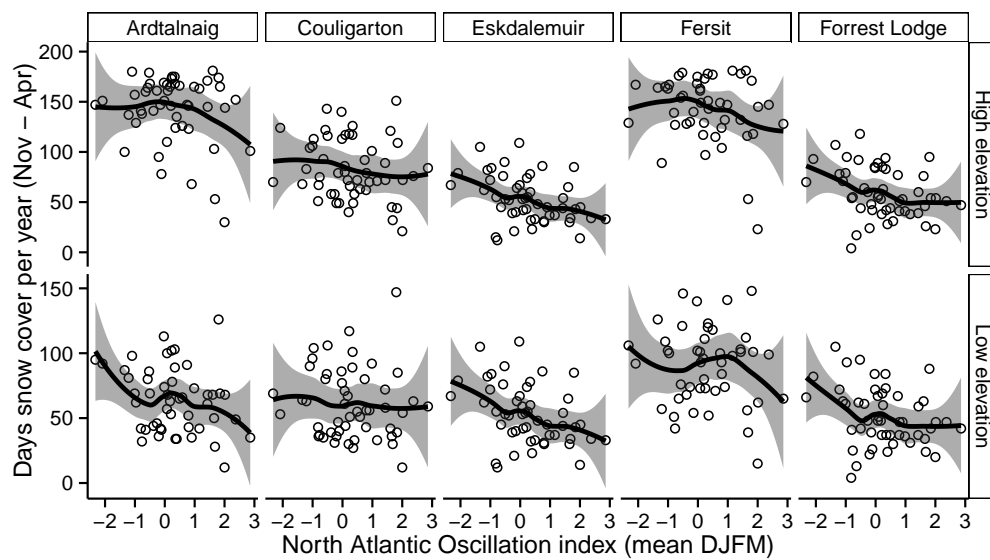


Figure 7: Long-record SSGB stations snow cover plotted against the NAO index, shown with a Loess and 95 % confidence bounds.

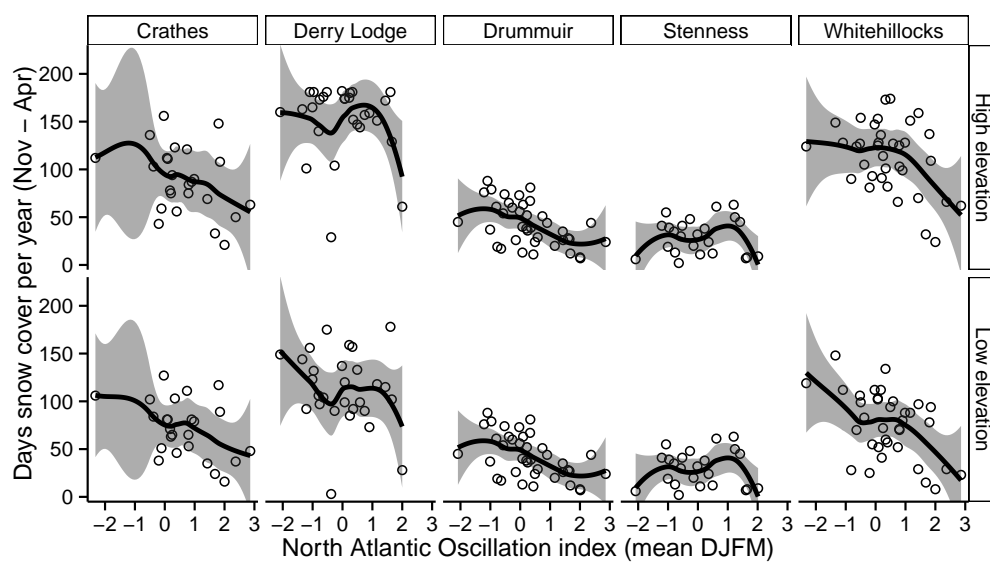


Figure 8: Eastern and Orkney SSGB stations snow cover plotted against the NAO index, shown with a Loess and 95 % confidence bounds.

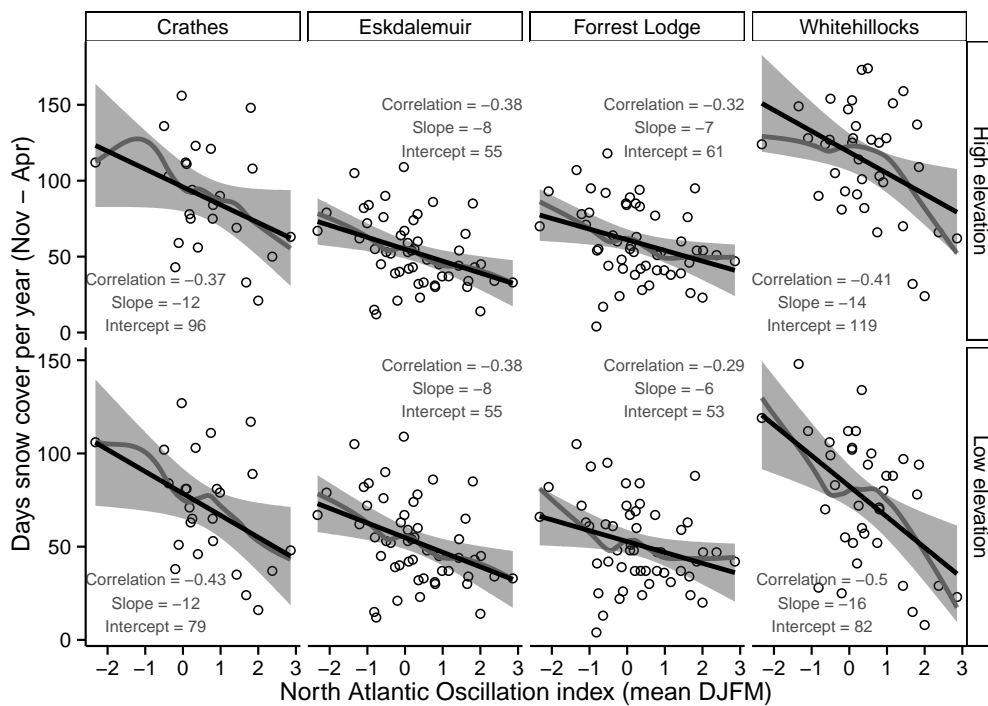


Figure 9: Comparison between days snow cover at select SSGB stations in years that reported all months between November and April and the NAO index. Shown with a linear model with 95 % confidence bounds and a Loess smoother (dark grey) for comparison.

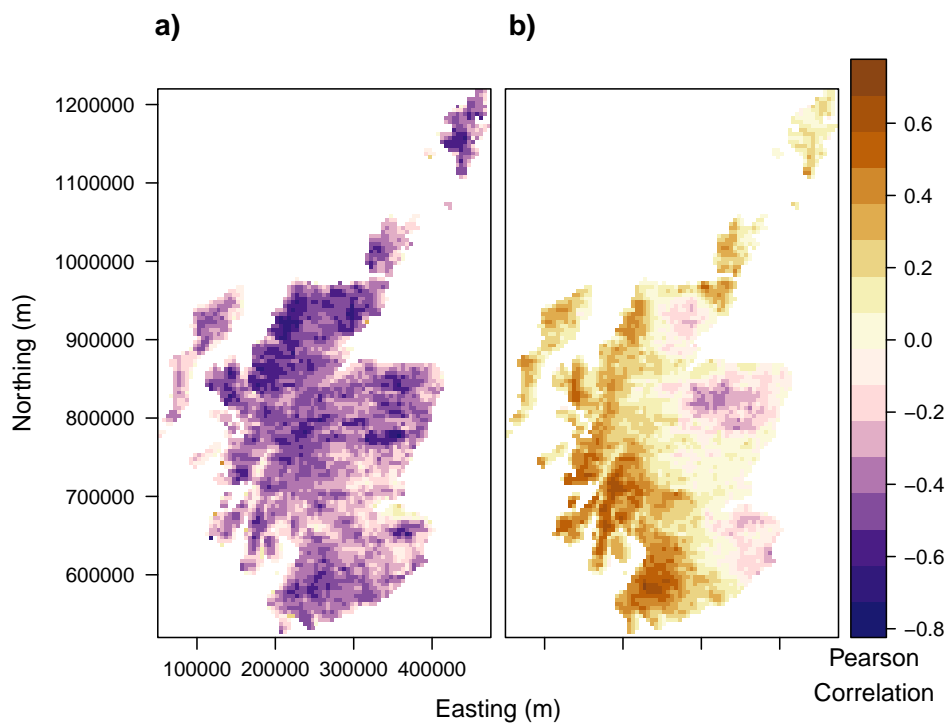


Figure 10: a) Correlation between number of days MODIS recorded snow cover each winter (Nov to Apr) and the mean DJFM NAO index. b) Correlation between number of days MODIS recorded cloud cover each winter (Nov to Apr) and the mean DJFM NAO index.